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I. Publications

We published two journal articles, one review article, and two conference papers acknowledging the support of NASA Heliospheric Physics Program under grant NAGW-1595.

Whang, Y. C., and L. F. Burlaga, Simulation of period doubling of recurrent structures, Journal Geophysical Research, 95, 20,663-20,671 (1990).
Whang, Y. C., S. L. Liu, and L. F. Burlaga, Shock Heating of the Solar Wind Plasma, Journal Geophysical Research, 95, 18,769-18,780 (1990).
Whang, Y. C., S. L. Liu, and L. F. Burlaga, Shock Heating of the Solar Wind Plasma, Physics of the Outer Heliosphere, Edited by S. Grzedzielski and D. E. Page, Pergamon Press, New York, pp. 241-244 (1990).
Whang, Y. C., and L. F. Burlaga, Radial Evolution of Interaction Regions, Physics of the Outer Heliosphere, Edited by S. Grzedzielski and D. E. Page, Pergamon Press, New York, pp. 245-248 (1990).
Whang, Y. C., Shock interactions in the outer heliosphere, Space Science Reviews, 57, 339-388 (1991).

II. Description of the Research

- o Using the r,t shock interaction model to study the radial evolution of large-scale solar wind structures at low heliolatitudes in the outer heliosphere.
- o Studied the period doubling of the 1974 recurrent solar wind structure. The structure evolved from two CIRs per solar rotation at 5 AU to one MIR per solar rotation outside 10 AU.
- o Showed that shocks are responsible for heating of the solar wind.
- o Published an invited paper in Space Science Review.

An r,t simulation code was developed in 1984 to study the evolution of large-scale solar wind structures at low heliolatitudes in the outer heliosphere. The simulation model uses the exact Rankine-Hugoniot relations to describe the jumps in flow properties at all shock crossings and treats shocks as surfaces of discontinuity with zero thickness. The model is known as the shock interaction model. The model has been used to carry out a series of simulations for the radial evolution of large-scale solar wind structures in the outer heliosphere [Whang and Burlaga, 1985a, b, 1986, 1988, 1990] and to simulate the heating of the solar wind in the outer heliosphere [Whang et al., 1990]. The research has been reported in 15 publications in the past 7 years.

A typical simulation is to study the evolution of the solar wind structure represented by an input function generated from solar wind measurements along the trajectory of a spacecraft. Numerical solutions of the MHD equations are carried out to describe step by step the evolution of the input solar wind in the region beyond the trajectory of the spacecraft. Observations are made only along a few limited trajectories, but computer simulation can supplement these by providing the detailed information on the evolution and interaction of large-scale solar wind structures in the vast region not directly observed.

Our shock interaction model is the only model that uses the Rankine-Hugoniot relations to calculate jumps in flow properties at all shock crossings. The shock interaction model has many important features including: (a) The model can calculate shock speeds which are needed to trace the trajectories of shocks in the outer heliosphere. (b) The model can calculate entropy increases across shocks which are responsible for the heating of the solar wind plasma. (c) The model can quantitatively handle the collision and merging of shocks.

The r,t code of the shock interaction model has been very successful in predicting the formation and evolution of CIRs and MIRs at low heliolatitudes. For example, the simulation of the November 1977 event shows a good agreement between the model prediction and observations [Whang and Burlaga, 1985b]. In a three-month period starting November 1977, the same solar wind was observed by IMP 7 and 8 at 1 AU, Voyager 1 and 2 at 1.4 AU, and Pioneer 10 at 15 AU. Our simulation used an input function generated from the IMP data. The predicted solar wind structures at 1.4 AU and at 15 AU agree very well with the observations made from Voyager and Pioneer.

II.A. Evolution of Solar Wind Structure Between 5 and 20 AU

The paper entitled "Simulation of period doubling of recurrent structures" presented a simulation study for the evolution of a recurrent solar wind structure between 5 and 20 AU using the r,t code of the shock interactions model. In 1974, IMP, Pioneer 10 and Pioneer 11 observed the radial evolution between 1 AU and 6 AU of a recurrent solar wind structure over five solar rotations. The recurrent solar wind consisted of two streams per solar rotation at 1 AU. The evolution process substantially modified the solar wind structure, the solar wind at 5 AU consisted of two CIRs per solar rotation.

The simulation study extrapolated our understanding of the recurrent structure between 5 and 20 AU. The input functions were generated from 140 days of plasma and magnetic field data observed by Pioneer 11. The simulation showed that between 5 and 20 AU the recurrent structure has evolved from a structure of two CIRs per solar rotation to a new structure of one MIR per solar rotation. Period doubling occurred near 10 AU when the two CIRs coalesced to form one MIR. The large-scale solar wind structure outside 10 AU bear virtually no resemblance to the parent stream structure near 1 AU.

II.B. Shock Heating of the Solar Wind Plasma

The radial gradient in the proton temperature reported by Mihalov and Wolfe [1978] provided the first evidence for the heating of the solar wind outside 1 AU. Plasma data observed by Pioneer and Voyager have been studied to show that a mechanism is needed to heat the solar wind in the outer heliosphere [Mihalov and Wolfe, 1978; Gazis and Lazarus, 1982; Kayser et al., 1984; Whang et al., 1989]. We used observational data and a simulation model to study the role played by shocks in heating the solar wind plasma in the outer heliosphere.

Entropy is a convenient thermodynamic parameter for studying the heating of the solar wind. The entropy per proton is

$$S = k \ln (T^{1.5}/n)$$

where $k = 1.38 \times 10^{-23}$ J/K is the Boltzmann constant, T is the proton temperature in degrees Kelvin, and n is the number of protons per cubic centimeter. Using a very large data base from Voyager 1 and 2 and Pioneer 10 and 11, we calculated the yearly averages of the solar wind entropy in 1972-1983 between 1 and 30 AU. The result showed that when r increases by a factor of 10 the average entropy increases by (3.81 $\pm$ 1.02) x 10^{-23} J/K/proton.

MHD shocks and interaction regions are important components of the solar wind structure in the outer heliosphere. When a shock propagates through the solar wind, the shock heats the plasma. We studied 413 shocks observed from Voyager and Pioneer in 1973-1983 to assess the shock heating. A majority of the strong shocks were observed between 3 and 6 AU. The average entropy jump across a shock increases with r outside 1 AU, reaches a maximum near 5 AU, and then decreases with r beyond 5 AU. The average entropy increases across shocks during low solar activity are slightly greater than those observed during high solar activity. When an average shock propagates through the solar wind, shock heating increases the entropy of the solar wind protons by ~0.8 x 10^{-23} J/K/proton.

We used the r,t code of the shock interaction model to calculate the heating of the solar wind in three simulation studies: (a) simulation of the November, 1977 event; (b) simulation of the recurrent solar wind structure in 1974; and (c) simulation of an idealized recurrent structure outside 14 AU. The results show that the calculated radial increases in average entropy are in good agreement with the increases in the long-term averages of the entropy observed on a global scale. Since shock heating is the only heating mechanism included in the shock interaction model. The good agreement between the simulation results and observations suggests that shocks are chiefly responsible for the heating of the solar wind plasma in the outer heliosphere at least up to 30 AU.

II.C. A Review Article

We published an invited paper entitled "Shock Interactions in the Outer Heliosphere" in Space Science Reviews (50 pages). The paper reviewed recent progress in simulation studies of the nonlinear evolution of the solar wind structure outside 1 AU, and in particular concentrated on the theoretical development and applications of the shock interaction model.

We first reviewed various simulation models including the gasdynamic model by Hundhausen, the MHD model by Steinolfson and Dryer, the corotational models by Pizzo and by Whang, and the kinematic model by Akasofu. These models have been used to simulate the evolution of isolated streams and the formation and propagation of corotating and transient shocks. Then we reported the r,t shock interactions model introduced in 1984 to study the evolution of large-scale solar wind structures at low heliolatitudes in the region outside 1 AU up to several tens of AU.

The review reported three principal applications of the r,t shock interaction model: (a) The basic interaction of a shock with the ambient solar wind, the formation and propagation of shock pairs, and the collision and merging of shocks. (b) To simulate the evolution of large-scale solar wind structures in the outer heliosphere. The simulation results provide the detailed evolution process for large-scale solar wind structures in the vast region not directly observed. Two selected studies were reported. (c) To study the heating of the solar wind in the outer heliosphere. The model calculations support shocks being chiefly responsible for the heating of the solar wind plasma in the outer heliosphere at least up to 30 AU.